# PHENO 2008 SYMPOSIUM LHC Turn On

University of Wisconsin-Madison

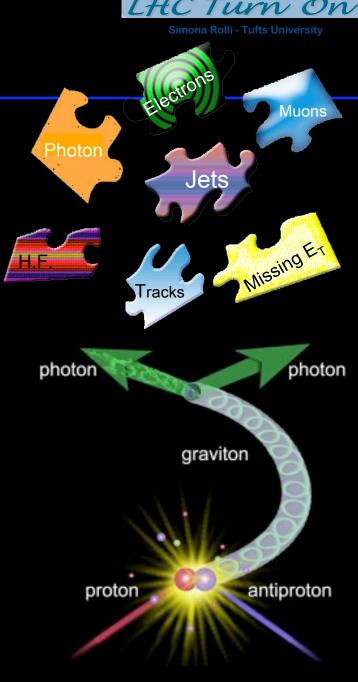
Search for New Physics at the Tevatron

Simona Rolli Tufts University (on behalf of the CDF and D0 Collaborations)



Outline of the talk

- TeVatron status
- Physics Processes and their signatures:
  - from simple objects to complex final states
    - leptons-only final states (and isolated tracks)
    - ... + Missing Energy and Photons
    - ... + Jets and heavy flavors
  - Specific model testing and global searches
- Final remarks and conclusions



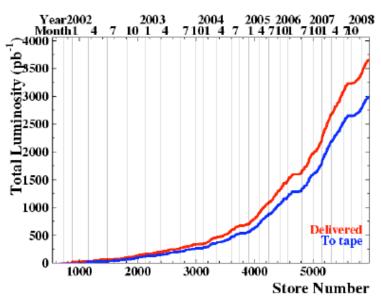


### **TeVatron Status**

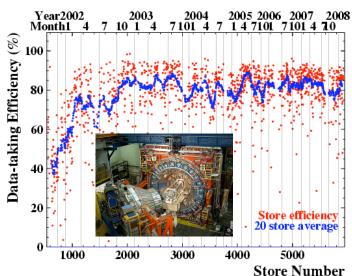
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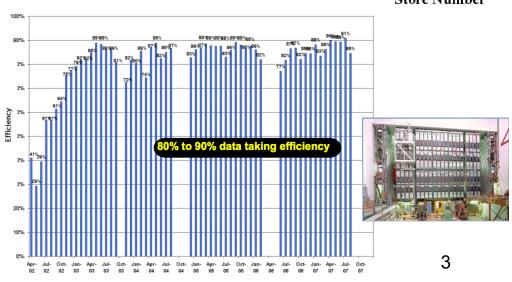
The TeVatron is doing very well!

#### Luminosity Profile



Delivered Lumi. > 3.6 fb<sup>-1</sup> Good for analysis ~ 3. fb<sup>-1</sup>







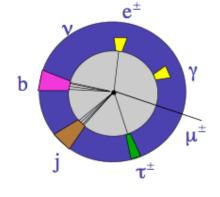
### Signatures and Physics Objects

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#### Physics Objects

- Tracks
- Jets
- Electron
- Photons
- Neutrinos
- Muons





#### Detector Components

- Tracking system
  - Large drift chambers
  - Precise Silicon detectors
- Calorimeters
- Muon Chambers

We study physics processes organizing them by their signature

#### Leptons-only final states

- e/μ identification well understood
- $\bullet$   $\tau$  id a little more complex
- Straightforward and highly efficient approach to search for anomalies

#### + Missing Energy and Photons

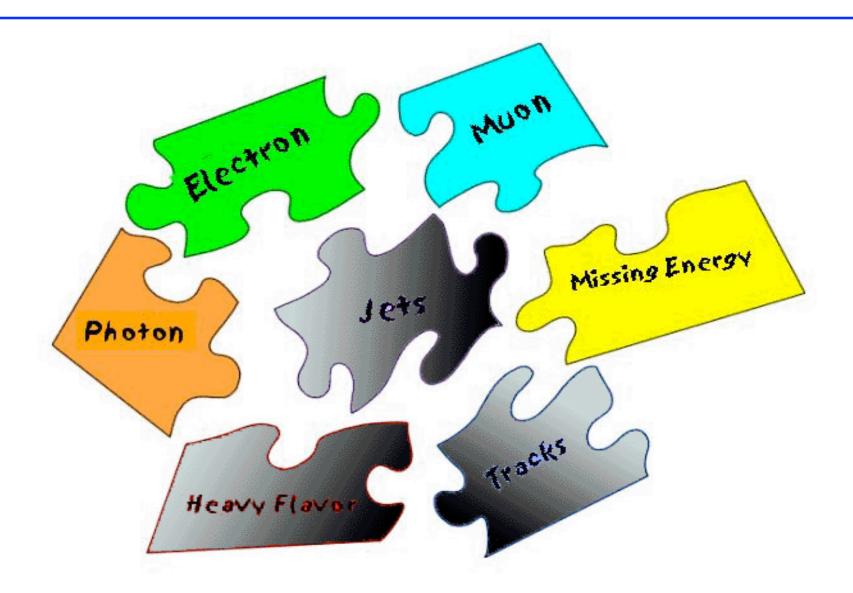
- Wealth of models and exotic processes
- Need accurate understanding of detector effects

#### •... + Jets and heavy flavors

- More complex signatures
- Maintaining high S/√B



### Leptons, Photons and MET



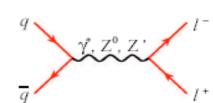


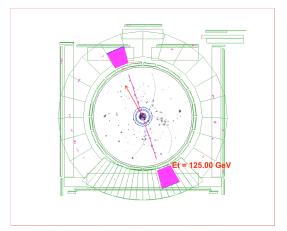
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### Searches in dilepton final states

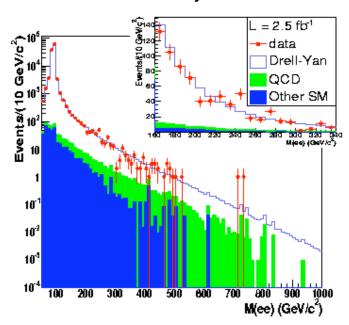
#### Old fashion mass bump hunt...

Z production and decay into ee/ $\mu\mu$  is precisely measured at the TeVatron (standard candles) Lepton ID/Reco and Trigger efficiencies are high and very well understood Background is low and easily determined (QCD fakes) Clean events





#### CDF Run II Preliminary



At CDF the dielectron mass spectrum is scanned in search for excesses in above 150 GeV/c<sup>2</sup>

The largest discrepancy shown by an unbinned maximum likelihood ratio is  $3.8\sigma$  in the range 228 - 250 GeV

 0.6% probability of seeing this size discrepancy in the range 150-1000 GeV



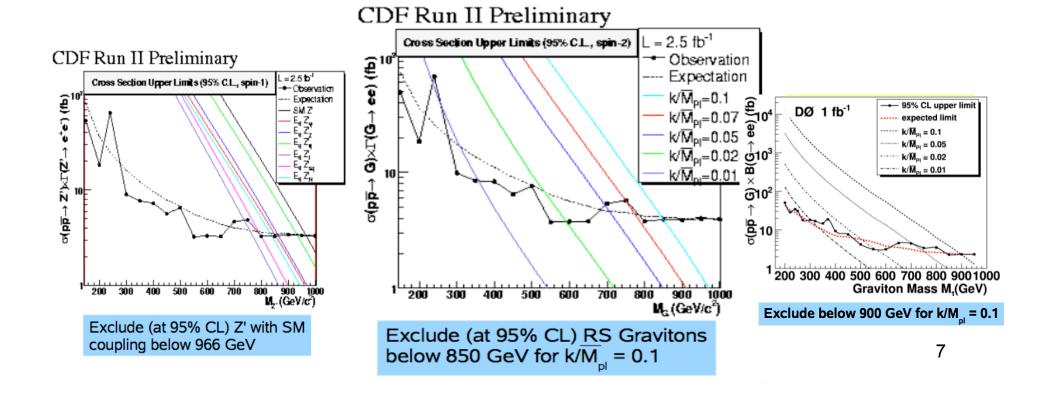
### Testing different models

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Once the data spectrum is well understood in terms of SM background, from MC, the acceptances for resonant states for different spin particles are derived (Z', RS Graviton) and the expected number of BSM events is calculated.

In the absence of an excess of data, 95% CL limits on production cross-sections and mass of the particles are set.

Similar results in µµ channel





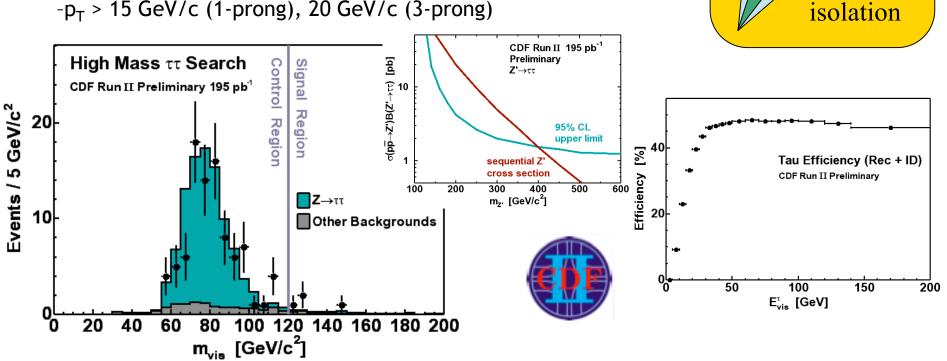
### Tau final states

τcone

 $\tau_h ID$ 

Ditaus final states are selected where

- •One tau decays leptonically:  $e/\mu$  (CDF)  $\mu$  (DØ) (plus v's)
- • $p_T > 10 \text{ GeV/c (CDF)}, p_T > 15 \text{ GeV/c (DØ)}$
- -Other tau hadronic (and  $v_{\tau}$ )
  - -One or three tracks ( $\Sigma q_{trk} = \pm 1$ ), opposite to lepton
  - -CDF: isolation 30°, shrinking  $\tau$  cone (10°  $\rightarrow$  3°)
  - -DØ: three types ( $\pi^{\pm}$ ,  $\pi^{\pm}\pi^{0}$ , 3-prong), NN score
    - •No electron veto (allows eμ)
  - $-p_T > 15 \text{ GeV/c (1-prong)}, 20 \text{ GeV/c (3-prong)}$

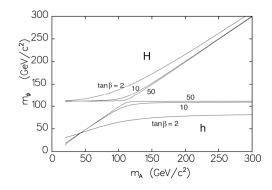




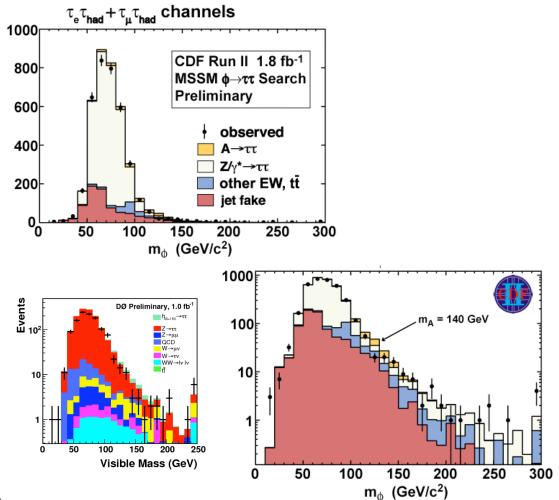
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## MSSM Higgs $\phi \rightarrow \tau \tau$

- In the MSSM framework the Higgs neutral sector simplifies at high tanβ
- A and h/H become degenerate



- Other scalar SM-like, low cross section
- Only need to search for a single mass peak (φ)
- For the A and its twin h/H, at high tan $\beta$  decays into b $\underline{b}$  (90%) and  $\tau\tau$  (10%) dominate

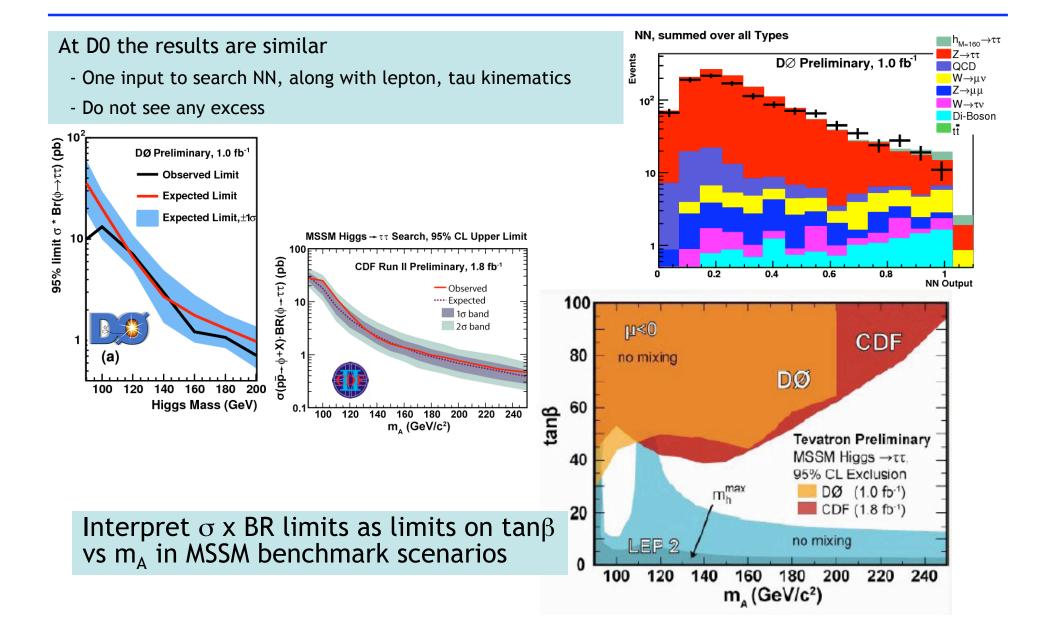


No excess in  $e/\mu + \tau_{had}$  channel (slight excess for CDF in 2007)



### $\phi \rightarrow \tau \tau$ Results

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# Multileptons final states: SUSY in Trileptons



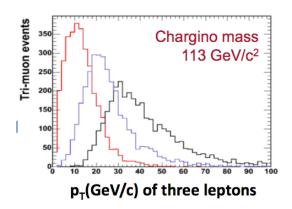
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Chargino Neutralino cascade decay results in a signature of (3 leptons or 2 leptons + track) and MET

Decays through W/Z favorable for heavy sleptons, but BR to leptons low

Decays through sleptons guarantee final leptons, but also preference to  $\widetilde{\tau} \rightarrow \tau$ 

CDF includes isolated tracks to reconstruct some of the hadronic taus The  $P_{\tau}$  of the leptons can be really low (CDF considers leptons up to 5 GeV/c)



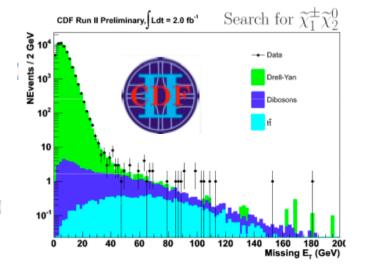
#### Selection (signal region):

- p<sub>T</sub> (15,10/5,5) GeV/c
- MET>20 GeV (DY and QCD rejection)
- N<sub>iets</sub> ≤ 1 and H<sub>T</sub> < 80 (top rejection)</li>
- Z-mass veto (DY rejection)
- Dilepton Mass above 20 GeV/c² (QCD and resonance rejection)

#### Trilepton backgrounds:

DY+fake, Z+y, diboson

Similar cuts at D0





### SUSY in Trileptons

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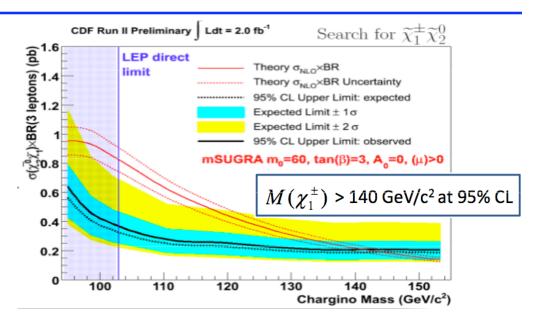
- Control regions in MET vs M<sub>ee</sub> phase-space
- Signal region is investigated only after validating backgrounds in control regions (a blind analysis)
- Good agreement with SM background

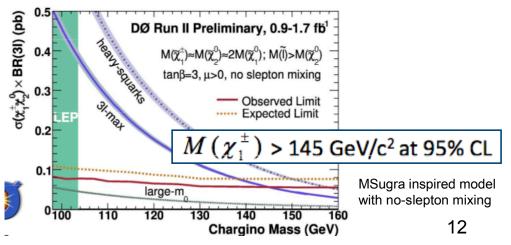
CDF Run II Preliminary,  $\mathcal{L} = 2.0 \text{ fb}^{-1}$ 

Analysis	Backg.	Signal	DATA
Trilepton	$0.9 \pm 0.1$	$4.5 \pm 0.6$	1
Dilepton+Track	6.9 ± 0.9	5.5 ± 1.1	6

DØ Run II Preliminary,

Analysis	£	Backg.	Signal	DATA
	(fb)			
ee+€	0.6	$\textbf{1.0} \pm \textbf{0.3}$	0.5 - 0.2	0
μμ+θ	1	<b>0.3</b> <sup>+0.7</sup> <sub>-0.03</sub>	0.5 – 2.5	2
еµ+€	1	0.9+0.4	1-4	0
ee+€	1.1	0.8 ± 0.7	1.7 – 4.7	0
$\mu^{\pm}\mu^{\pm}$	0.9	1.1 ± 0.4	0.6 – 3.7	1





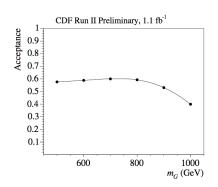
## Multilepton final states: LED in ZZ



#### eeee final state

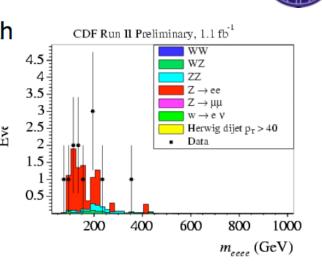
To maximize lepton identification efficiency isolated track electron candidates are considered and some of the most stringent ID requirements for high  $P_T$  electrons are released.

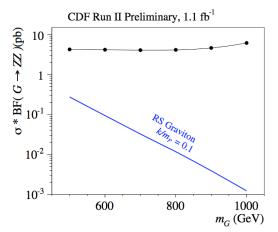
High signal efficiency is obtained for RS Graviton model (40-60%)



### Estimate background from data

Use low-mass eeee
 events and events with
 hadronic fakes,
 extrapolate to signal
 region





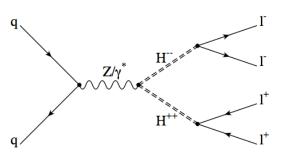
Limit still above theory

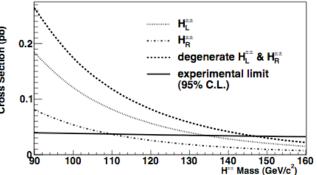
# Multi leptons final states: Doubly Charged Higgs

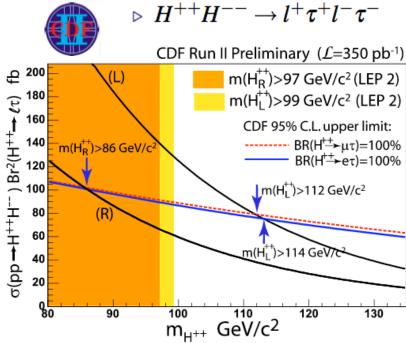


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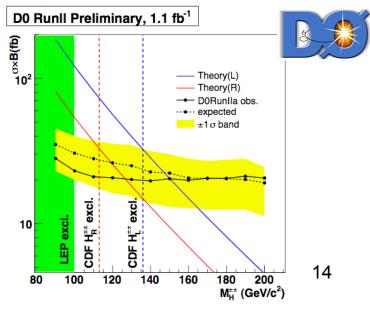
#### 4 leptons final state











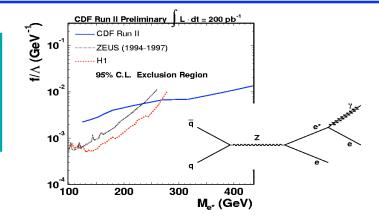
## Lepton+γ final states: Excited leptons



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Observation of excited states of quarks and leptons might confirm the hypothesis that they are not elementary particles, but composite states

Select events with eey  $(\mu\mu\gamma)$  in the final state and look for resonance in  $M(e\gamma)$  or  $M(\mu\gamma)$ 

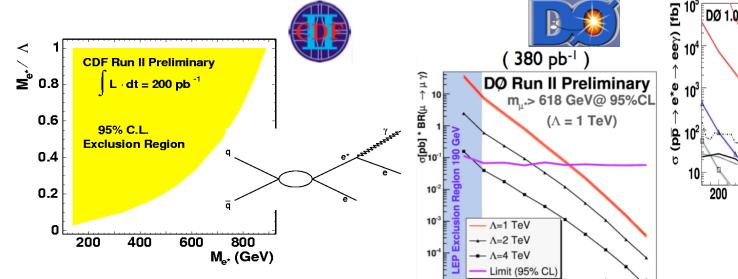


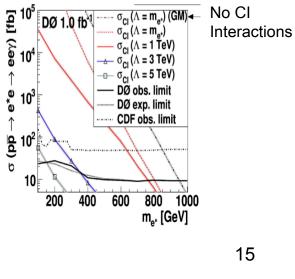
At Tevatron,  $e^*/\mu^*$  can be produced via contact interactions or gauge mediated interactions

400

800

m\_[GeV]

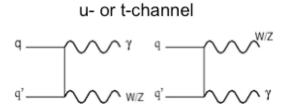


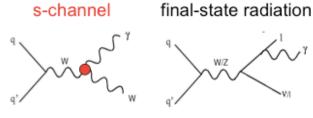


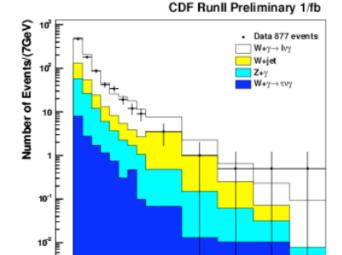
## Lepton+γ+MET final states: W<sub>γ</sub> and Z<sub>γ</sub>



#### Test of gauge couplings (as predicted by the SM) and a window on new physics



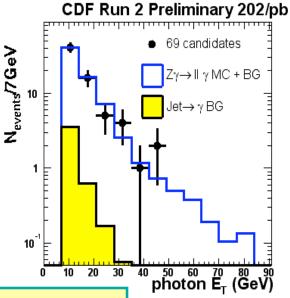




80 100 120 140 160 180 200

Photon E<sub>T</sub> (GeV)

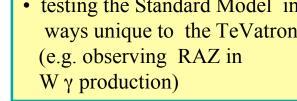




Now V+y cross-sections well established, we are:

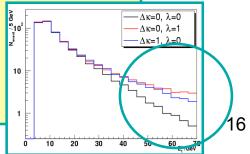
• optimizing sensitivity to anomalous coupling and new physics

• testing the Standard Model in ways unique to the TeVatron (e.g. observing RAZ in





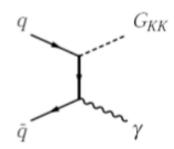
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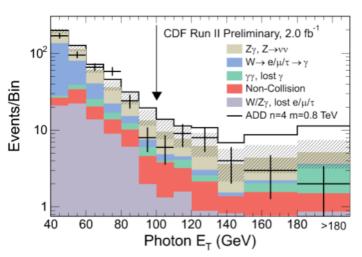




### γ+MET final states: LED

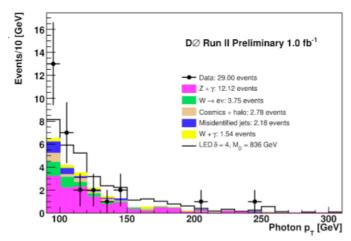






CDF RunII Preliminary, 2.0 fb <sup>-1</sup>					
N LED	α (%)	$\sigma_{obs}^{95}$ fb	$M_D^{obs}$ GeV		
2	7.2	84.7	1080		
3	7.2	84.7	1000		
4	7.6	80.4	970		
5	7.3	82.7	930		
6	7.2	84.4	900		

A Kaluza-Klein graviton is produced in association with a photon. The graviton escapes detection, leaving a monophoton signature in the detector



Number of extra dimensions	95% CL Limit on Fundamental Mass Scale (M <sub>D</sub> ) (GeV)
2	884
3	864
4	836
5	820
6	797
7	797
8	778



### Diphotons:LED

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- •The search for new particles decaying to diphotons uses the RS graviton model to express sensitivity to Kaluza-Klein graviton resonances
- Randall-Sundrum graviton model

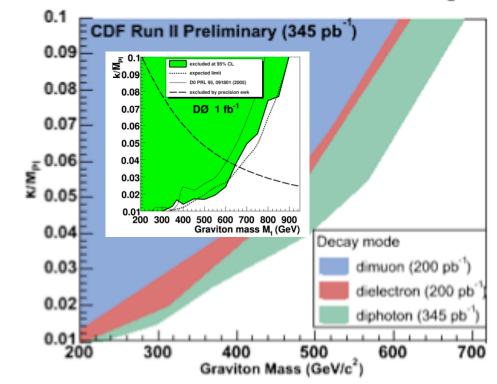
4-dimensional metric multiplied by warp factor

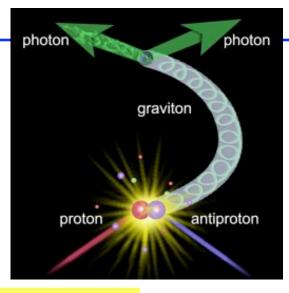
The coupling of individual KK states to matter is set by the weak scale

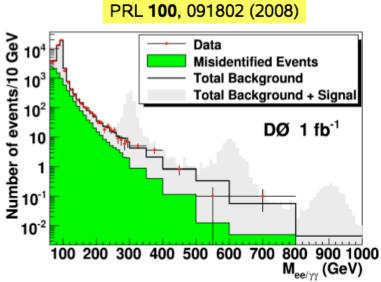
(parameters :  $M_G$  and  $k/M_{P lanck}$ )

KK states can be observed as spin 2 resonances

#### RS Graviton Searches, 95% C.L. Exclusion Regions







Combined with dilepton searches





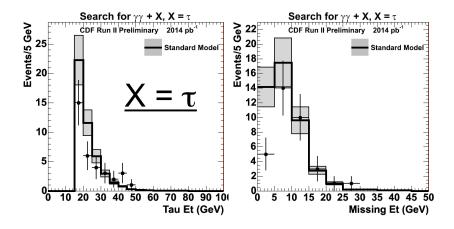


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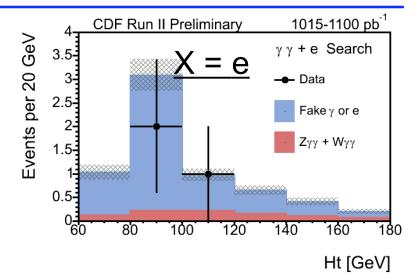
#### Search for yy + X

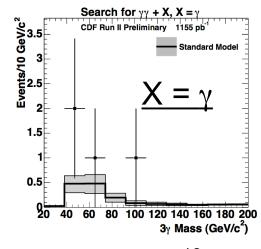
Nominal high  $E_T$  object identification and kinematic selections are used.

The observed event counts is reported as well as SM prediction for various kinematic distributions



Data driven bkg estimate (fake  $\tau$ )



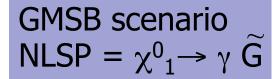


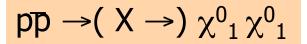
Good agreement between data and SM predictions
- Continue to add objects in γγ+X Search



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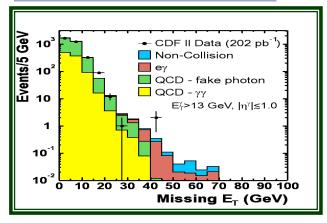
### diphoton + MET: GMSB SUSY



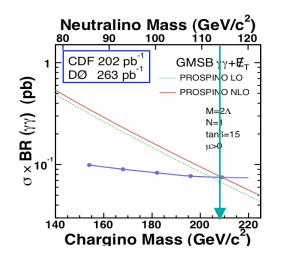


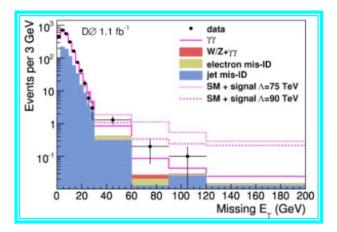


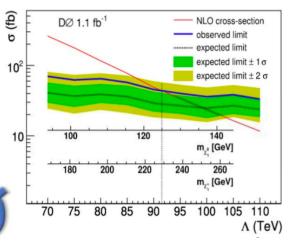
$$2 \gamma + E_T$$

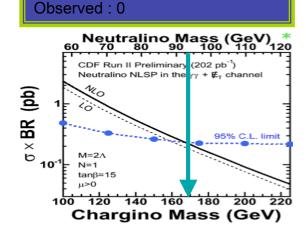












For Missing Energy > 45 GeV

Expected: 0.60 ± 0.50



### Adding jets and flavor tagging







### Jets and Heavy Flavor

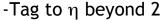
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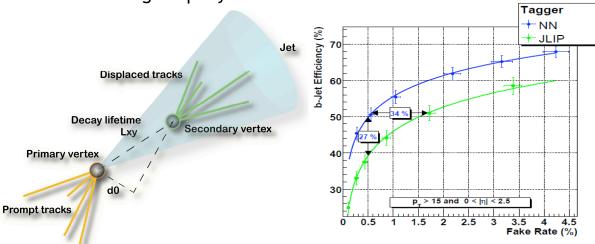
Hadronic jets are reconstructed using several algorithms: Cone, Midpoint, KT etc..

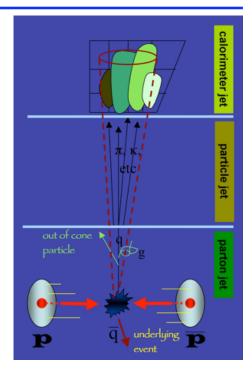
Measured jet energies are corrected to scale them back to the final state particle level jet . Additionally there are corrections to associate the measured jet energy to the parent parton energy, so that direct comparison to the theory can be made. Currently the jet energy scale is the major source of uncertainty in the measurement of the top quark mass and inclusive jet cross section

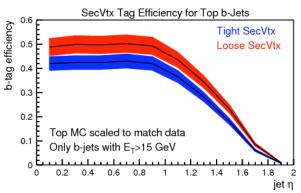
#### B-jet identification is implemented via:

- -displaced vertices with  $L_{xy}/\sigma$  cut (CDF)
- -Vertex mass separation (CDF)
- -combining vertex properties and displaced track info with NN (D0)











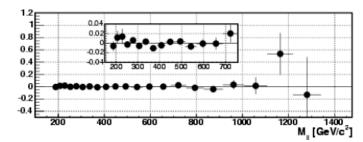
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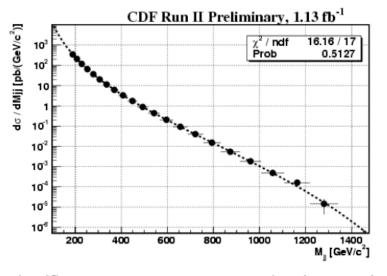
### Dijets final state: mass bumps

#### Another mass bump hunt...

- Choose events with two high $p_{_{\!\scriptscriptstyle T}}$  jets with rapidity less than 1.0. Look for an excess in the dijet mass spectrum for masses above 180 GeV
- Possible signals include excited quarks, W', Z', and Randall-Sundrum gravitons
- Find functional form of of dijet spectrum in pythia and herwig, fit to data. Look for "bumps" in the data minus fit plot

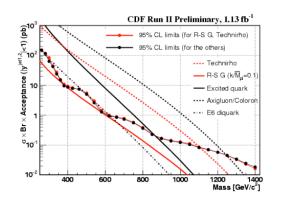
(Data - Fit) / Fit

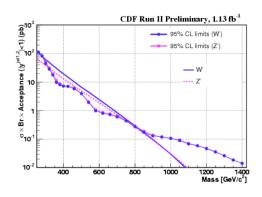






- No significant resonant structure is observed, so limits are set on various models
- Excludes (at 95% CL) excited guarks from 260-870 GeV, W' from 280-840 GeV, and Z' from 320-740 GeV

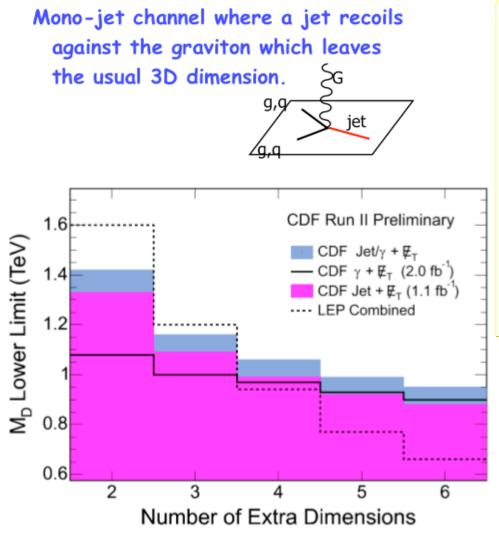


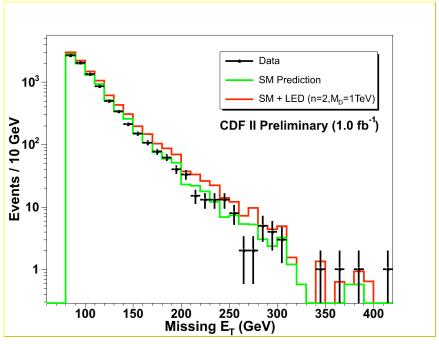




### Single jet + MET: LED

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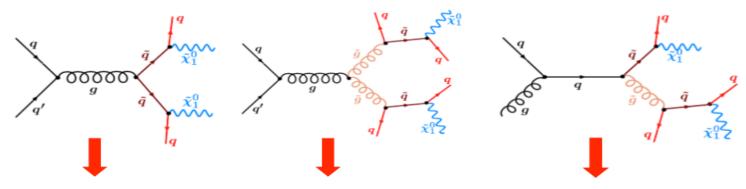




# MET + jets: SUSY squarks and gluinos



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Result: 2 jets and MET Result: 4 jets and MET Result: 3 jets and MET

> Although the production is strong, the analyses are challenging due to QCD-multijet and W/Z+jet backgrounds

Solution: break-down analyses in jet-multiplicity bins and optimize separately (using MET and HT $\leftarrow$  Sum of jet  $E_{\tau}$ )

Lepton veto Δφ jet-MET QCD bckg from low MET data

#### CDF Run II Preliminary, $\mathcal{L} = 2.0 \text{ fb}^{-1}$

#### (hep-ex/0712.3805, PLB 660, 449 (2008))

Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA
Dijet	325	225	35,35	<b>11</b> ± 1 +3/-2	11
Trijet	375	175	35,35,35	<b>11</b> ± 1 +3/-2	9
4-jet	400	100	35,35,35,20	<b>18</b> ± 1 +6/-3	20

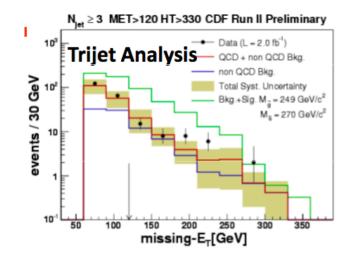
Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA
Dijet	330	180	165,100	16 ± 5	18
Trijet	330	120	140,100,25	37± 12	38
4-jet	280	90	95,55,55,25	48 ± 17	45

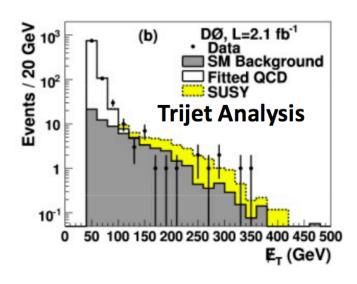
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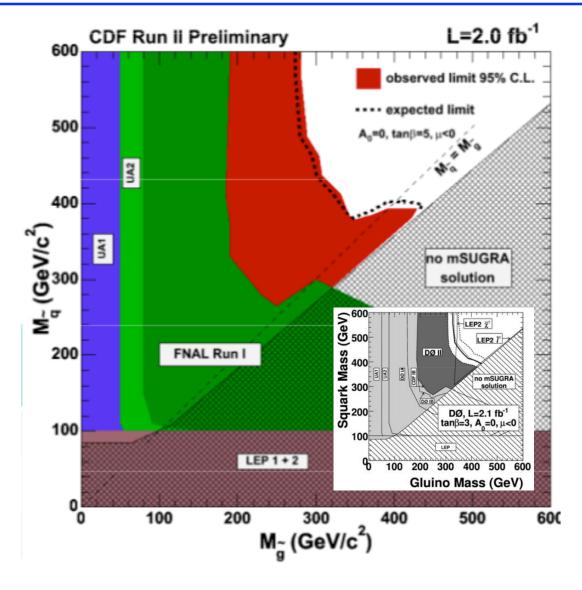


### SUSY in MET + jets

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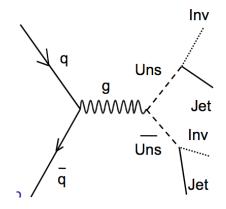








### Jets+MET final state



The analysis is a counting experiment examining two different kinematic regions (each region being more sensitive to different models). Cuts are not optimized for a specific model.

#### Main backgrounds:

- $-Z \rightarrow v v + jets$  (irreducible background)
- $-W \rightarrow Iv + jets$  (with charged lepton lost)
- -Residual QCD and non-collision backgrounds.

- Leptoquark models
  - LQ pairs, each decaying to quark and neutrino.
- MSSM (non-mSUGRA, R-parity conserved)
  - •Squark pairs, each decaying to quark and neutralino.

#### Data driven extrapolation

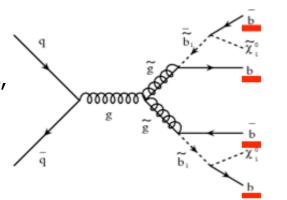
Background	125/80	225/100
<b>Z</b> → νν	777 ± 49	71 ± 12
$W \rightarrow \tau \nu$	669 ± 42	50 ± 8
$W \rightarrow \mu \nu$	399 ± 25	33 ± 5
<b>W</b> → <b>e</b> v	256 ± 16	14 ± 2
Z → II	29 ± 4	2 ± 0
QCD	49 ± 30	9 ± 9
γ + jets	55 ± 13	5 ± 3
top	74 ± 9	11 ± 2
non-collision	4 ± 4	1 ± 1
Total	2312 ± 140	196 ± 29
Observed	2506	186

4	<b>.</b> •	<b>A</b>	
MET			
100			
80			-
Į	105	005	-
	125	225	HT

# HF final states: sbottom from gluinos



If the sbottom is significantly lighter than the other squarks, the two body decay of gluino into bottom/sbottom is kinematically allowed



The sbottom decays into a bottom and LSP, giving rise to a final state with <u>4</u> b-jets and missing energy

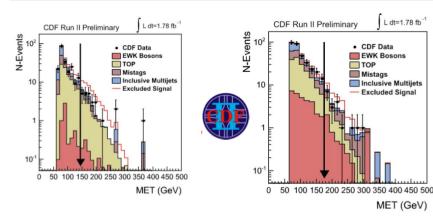
The analysis is optimized for 2 points in the SUSY parameter space:

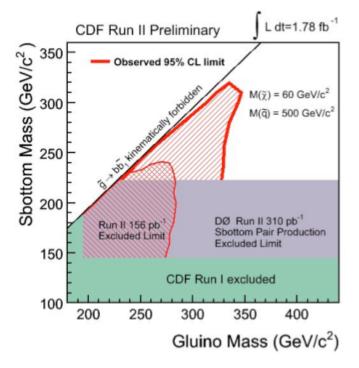
#### Large $\Delta m$ between $\tilde{g}$ and $\tilde{b}$

 $M(\tilde{g}) = 320 \text{ GeV/c}^2$ ,  $M(\tilde{b}) = 250 \text{ GeV/c}^2$ ,  $M(\tilde{\chi}) = 60 \text{ GeV/c}^2$ 

#### Small $\Delta m$ between $\tilde{g}$ and $\tilde{b}$

 $M(\tilde{g}) = 300 \text{ GeV/c}^2$ ,  $M(\tilde{b}) = 280 \text{ GeV/c}^2$ ,  $M(\tilde{\chi}) = 60 \text{ GeV/c}^2$ 

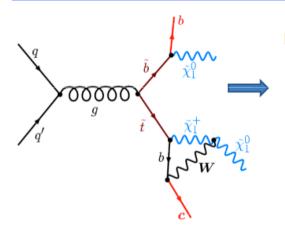






### Stop searches



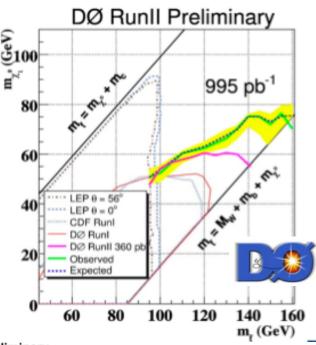


Light stop and sbottom production and decay

#### Stops to charm

- Exactly 2 jets (reduction of QCD)
- Jet pt cuts (20,40 GeV/c) and angular separation of jets (reduces QCD and W+jets)
- Angle between jets and met (reduction of QCD)
- Flavor tagging using Neural Network (impact parameter, secondary vertex information)

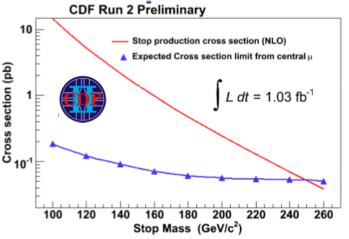
Exclusion: stop mass <149 GeV/c2 for neutralino mass of 63 GeV/c<sup>2</sup>



Other option is that stop does not decay in the detector (CHAMP)

- Slow particle signature: slowly-moving highly-ionizing highly-penetrating particle
  - Will look like muon with possible calorimetry energy deposition
- Goal: Measure Time of Flight mass of tracks

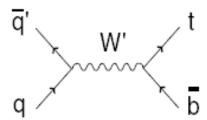
Stable stop mass > 250 GeV/c<sup>2</sup> at 95% CL



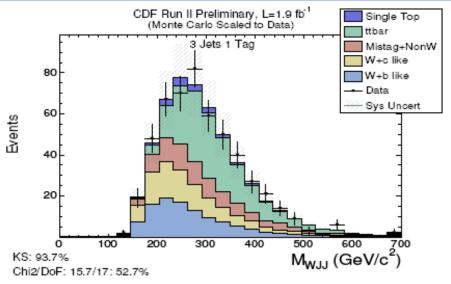
# Heavy flavor final states: W'→ tb



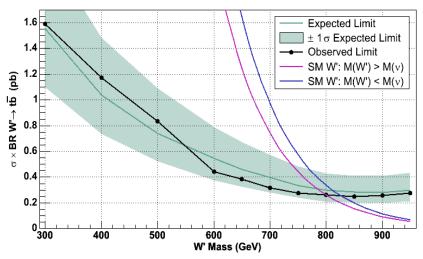
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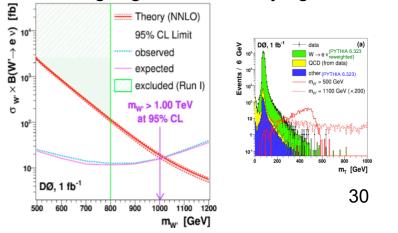
Search for resonant tb(+cc)
pair production
In W+2 jets and +3 jets
channels (semileptonic W),
look for unexpected structure
in M(Wjj)



95% C.L. Observed Limit - CDF Run II Preliminary: 1.9 fb<sup>-1</sup>



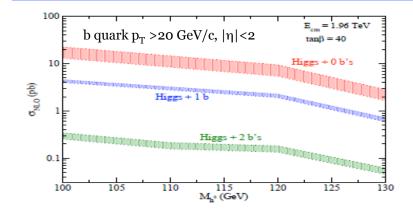
#### Extra W gauge boson decaying into ev



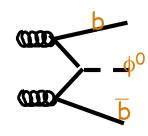


### HF final states: φ→bb

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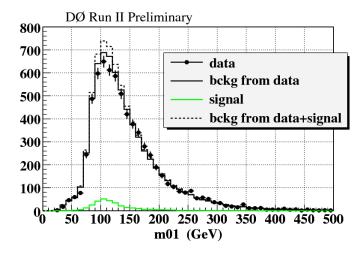


Inclusive  $H \rightarrow b\underline{b}$  is too hard due to QCD background

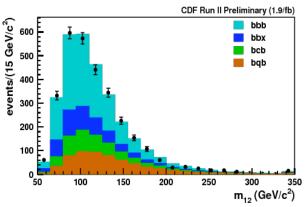


Require one additional bottom quark jet besides the two from Higgs decay

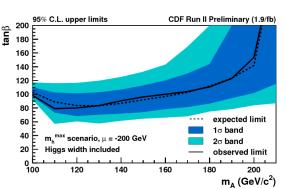
"3b" channel best compromise between signal and background rates



Search uses invariant mass of the two leading jets m<sub>01</sub> in triple-tagged events No excess observed



Search in mass of two lead jets m<sub>12</sub> No excess observed



31

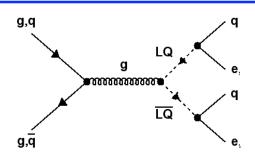


### More complex signatures: leptoquarks

Leptoquarks (LQ) are hypothetical particles which appear in many SM extensions to explain symmetry between leptons and quarks



- superstring-inspired models
- 'colour' SU(4) Pati-Salam model
- composite models
- Technicolor
- They couple to leptons and quarks of the same generation
  - Decay is governed by Br(LQ→ql)



1<sup>st</sup> Generation
$$LQ \overline{LQ} \rightarrow e^{-}e^{+}q\overline{q}$$

$$LQ \overline{LQ} \rightarrow e^{\pm}v_{e}q_{i}q_{j}$$

$$LQ \overline{LQ} \rightarrow v_{e}v_{e}q\overline{q}$$

$$2^{nd}$$
 Generation
$$LQ \overline{LQ} \rightarrow \mu^{+}\mu^{-}q\overline{q}$$

$$LQ \overline{LQ} \rightarrow \mu^{\pm}v_{\mu}q_{i}q_{j}$$

$$LQ \overline{LQ} \rightarrow v_{\mu}v_{\mu}q\overline{q}$$

$$3^{rd}$$
 Generation
$$LQ \overline{LQ} \rightarrow \tau^{+}\tau^{-}q\overline{q}$$

$$LQ \overline{LQ} \rightarrow \tau^{\pm}v q_{i}q_{j}$$

$$LQ \overline{LQ} \rightarrow v_{\tau}v_{\tau}q\overline{q}$$

$$LQ LQ \rightarrow Ilqq$$
  
 $LQ LQ \rightarrow Ivqq$   
 $LQ LQ \rightarrow vvqq$ 

BR = 
$$\beta^2$$
  
BR =  $2\beta$  (1- $\beta$ )  
BR =  $(1-\beta)^2_{32}$ 



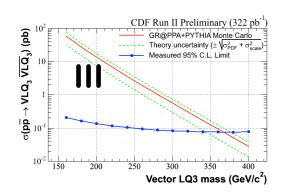
### Leptoquark Results

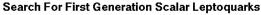
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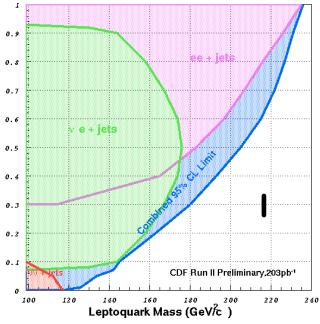
<u>Signature:</u> dilepton + jets, lepton + jets + MET, MET + jets <u>Analysis:</u> counting experiment

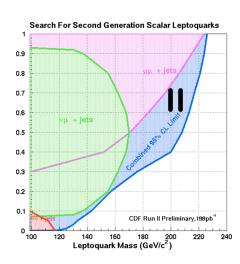
A series of cuts is applied in sequence with the goal of reducing the background (W/Z + jets and top) enhancing the signal retention

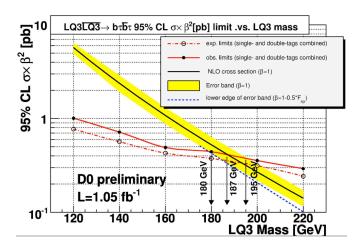
<u>Cuts are optimized</u> to give the maximum S/B Final number of events are compared with SM expectation <u>No excess -> limits on production cross section</u>











# More complex signatures: γ+b+jets+MET



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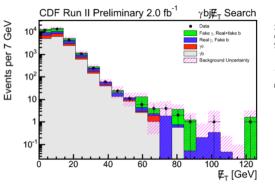
A handful of exotic processes would give rise to a final state signature comprising γ+b+jets+MET Many anomalies could be reduced to detector mis-measurements.

#### Selection:

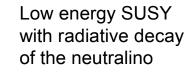
One high E<sub>T</sub> photon
≥ 2 jets
≥ 1 tagged jet
Large MET (> 25 GeV)
Topological cuts

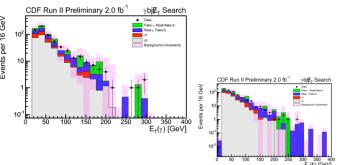
Main background (from data and MC)

·	Fake γ	Real γ	
Fake b-tag	Α	В	
Real b-tag	С	D	



Source	Number
γb	291 ± 7 (stat.) ± 50 (syst.)
γc	92 ± 25 (stat.) ± 45 (syst.)
Fake b, real γ	141 ± 6 (stat.) ± 30 (syst.)
Fake γ	113 ± 49 (stat.) ± 54 (syst.)
Total	637 ± 54 (stat.) ± 128 (syst.)
Data	617





	CDF Run II Preliminary 2.0 fb <sup>-1</sup>	γbj <b>⊭</b> <sub>T</sub> Search
Events per 24 GeV/C	101	Data Fake y, Real+fake b Real y, Fake b yc pt Background Uncertainty
		500 600 700 M <sub>bi</sub> [GeV/c <sup>2</sup> ]

### PHENO 2008 SYMPOSIUM LHC Turn On

### Final Remarks

- The results presented are by far not exhaustive
- Even when a <u>signature-based</u> approach is advocated, results are presented in the end as a function of specific models (typical case dilepton searches, high P<sub>T</sub> Z's etc)
- And when the result is presented as a testing of a model, there is always a check on control regions, defined by their signature...
- So, what is all this fuss about model-based and signature-based approaches?
- I believe that both are to be pursued in a balanced way: both have their pros and cons:
  - A) <u>Traditional model driven analyses</u>
    - pick a favorite theoretical model
- ® might become soon outdated!
- pick a process, choose the best signature(s): optimize selection acceptances based on signal MC
- · calculate the background

- best optimization!
- evaluate the limit or discovery your signal in timely fashion allows theory testing!
- B) Signature based approach
  - pick a specific signature ( i.e. diphoton+X)
- © open to a whole lot of models!
  - define your sample in terms of known processes 😢 Not the best optmization !
  - publish estimates of acceptances & cross section information useful for theorists ..but how much?? Detector effects are detector specific or we would all be using PGS! ;-)
  - see an excess? Inconsistency with SM? Test one or more models later ...(but the experiments will never release a controversial results for theorists to interpret, this is just sociology 101)
  - Quero-like access to the data? Is the astrophysical model suitable for HEP?

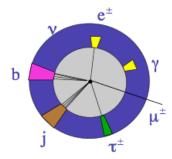


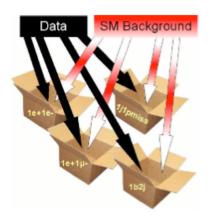
### Global Searches

The goal is to perform a model-independent global search of high  $P_T$  data:

- -study bulk features of high P<sub>⊤</sub> data;
- -search for resonances invariant mass distributions
- -search for significant excesses at high sum-p<sub>T</sub>

Physics objects are categorized and events selected and partitioned into ~400 exclusive final states





Pythia and MadEvent are used to implement the SM theoretical prediction (CdfSim emulates the detector response)

Many correction factors are used to obtain the *true* SM predictions (shouldn't a global search work globally?)

theory k-factors etc experimental efficiencies and Scale Factors, fake rates etc

# PHENO 2008 SYMPOSIUM LHC Turn On Simona Polli - Turts University

### **Global Searches**

#### **Shape Discrepancies**:

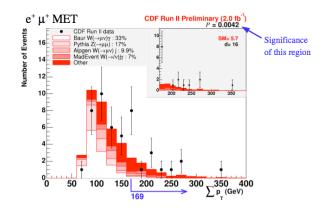
Most shape discrepancies caused by difficulty in modeling soft jet emission No claim of new physics can be motivated by such discrepancies <a href="Bump Hunter:">Bump Hunter:</a>

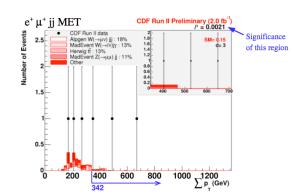
The significance is estimated via pseudo-experiments

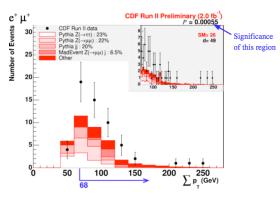
The only discovery level bump found is still to be attributed to the same bad modeling of QCD soft radiation

Excess of data at high sum-p<sub>T</sub>

A few final states gives some excess but only ~8% of hypothetical CDF experiments are expected to give a more interesting excess purely by chance









Many exciting results are currently produced at the Tevatron!

We are still the place of interest!

Many of the results interplay nicely:

from testing the SM processes to searches for Exotica

same signature, different physics

The experiments are working hard despite the dire budget situation

A bump can be around the corner before the LHC turns on...

